Ripple Dynamics and Benthic Transformations under Variable Wave Forcing

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LONG-TERM GOALS

Sand ripples that form under the action of waves/currents in coastal regions play a major role in sediment acoustics and are a main contributor to the seafloor roughness. An understanding of ripple dynamics is important for the description and modeling of various coastal processes such as underwater object scour/burial, local wave attenuation by bottom roughness and cross-shore sediment transport. While the focus of much of the previous (voluminous) work has been on the dynamics and evolution of bedforms under steady flow conditions and in homogeneous sediments, it has become increasingly clear that the variations of flow intensity and the heterogeneity of sediments play crucial roles in coastal circulation, benthic turbulence and bottom topography. The previous work on graded sediments has largely been associated with field observations or very small-scale (low Reynolds number) laboratory experiments under steady flow conditions, and they only dealt with bulk observations. The long-term goal of our research program is to create fundamental scientific knowledge that underpins the development of predictive tools for (oceanic) benthic transformations in heterogeneous media under variable flow forcing. The principal approach is to identify, investigate and parameterize critical hydrodynamic processes and parameters that govern the dynamics of benthic flow and morphological transformations using moderate and large-scale laboratory experiments, theoretical analyses and numerical simulations.

OBJECTIVES

The near-term objectives of our research are to: (i) study the dynamics and morphology of symmetric/asymmetric ripples generated under symmetric/asymmetric flow for both sustained and variable forcing and in homogeneous and heterogeneous sediments; (ii) investigate the processes responsible for ripples decay/degradation in homogeneous and heterogeneous sediments; (iii) study segregation processes frequently observed in the field but mostly overlooked in laboratory/theoretical studies; (iv) develop quantitative models for ripple formation, growth, transformation and decay under the above conditions; and (v) verify these models using laboratory and available field data.

APPROACH

A comprehensive laboratory experimental and theoretical research program was conducted to investigate the dynamics of sand ripples under conditions that mimic natural environments. The main

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components of the program were to: (i) measure, using moderate- and larger-scale experiments, the spatial variability of ripple morphology under oscillatory flow and shoaling waves; (ii) develop models/parameterizations for ripple morphology, including sediment sorting in heterogeneous sediment mixtures; and (iii) extrapolate laboratory findings, using appropriate dimensionless parameters, to oceanic conditions with the aim of providing guidance for the interpretation of field data and models development. The emphasis was on improving physical understanding and quantitative predictive skills of ripple morphology, evolution, decay and grain sorting.

WORK COMPLETED

Significant progress has been made during the course of our research program to develop a hierarchy of models of different complexity for ripple dynamics and scour/burial of bottom objects [1-9]. In FY 08, our research was focused mostly on: (i) ripple dynamics and bed transformations under variable flow intensity in homogeneous and heterogeneous sediments [10-12], (ii) grain segregation and sorting under steady/variable flow intensity in heterogeneous sediments [12,13], and (iii) ripple decay and degradation in homogeneous and heterogeneous environments [11,12,14]. In the experiments with homogeneous quartz sand, a 35 m long wave tank with shoaling waves along a sandy slope (see [2,3]) was used. Experiments with calibrated homogeneous and heterogeneous sediments (bimodal mixture of colored spherical glass beads) were conducted using a 15 m long flume with an oscillatory flow rig (see [11,12]). To model the effect of turbulence on ripple decay, an oscillating grid/plate assembly (Fig. 1) was placed in the flume to generate controlled turbulence [15].

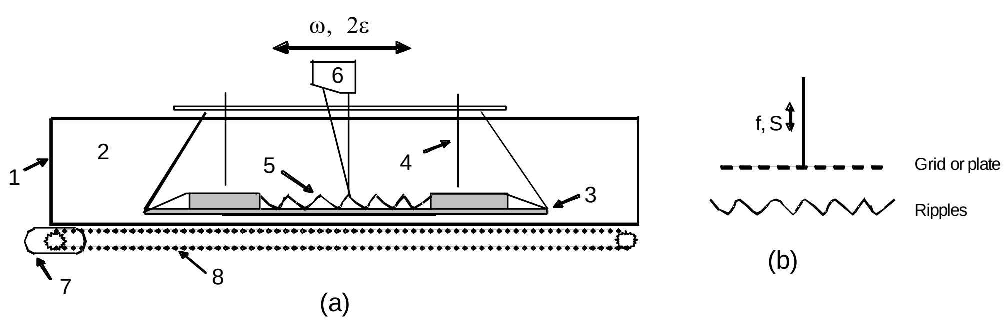

Fig. 1. A schematic of 15 m long experimental flume (a) and the oscillating grid assembly (b) to generate controllable turbulence. 1 - tank, 2 – water, 3 - oscillating rig, 4 – fixed to tank vertical barriers to damp surface waves, 5 - sand ripples, 6 - laser displacement sensor (LDS), 7 - computer controlled servo motor, 8 - chain to oscillate rig.

Both wave tank and flume facilities are equipped with state-of-the-art instrumentation for flow diagnostics, which include: wave gauges, three-component acoustic Doppler Velocimetry (ADV), high-precision Laser Displacement Sensor (LDS) for bedform mapping and high-resolution color photography and Particle Image Velocimetry (PIV) with high-speed (500 f/s) camera and IR laser to illuminate small nylon micro spheres to reduce the effect of sediment particles on PIV measurements (Fig. 2). The results obtained are described in [8-14], and the main FY 08 findings are summarized below.

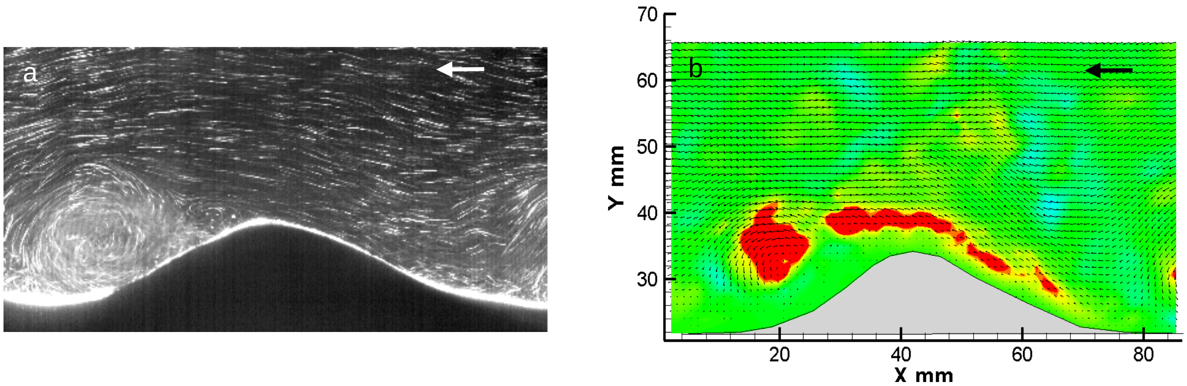

Fig. 2. A streak photograph (a) and PIV vorticity/velocity map (b) in an oscillatory flow over ripples of a bimodal sediment mixture. The flow moves from right to left (see arrow) and stops, generating an intense eddy. An IR laser was used to illuminate the tracked small nylon micro spheres thus reducing the effect of sediment particles on PIV measurements.

RESULTS

(i) For a bimodal sediment mixture of spherical grains of sizes d_1, d_2 and mass concentrations c_1, c_2= (1-c_1), the most important parameter is the effective grain size, $d^* = d_1 d_2 \sqrt{(c_1 d_2 + c_2 d_1)/(c_1 d_2^3 + c_2 d_1^3)}$, with the latter suitably defining the *rms* grain diameter in the mixture, taking into account the number of particles of different sizes in a unit mass of the mixture [11,12,14]. Using this parameter, our previous models/parameterizations for ripples in homogeneous sediments [1,3,5,9] were modified and tested in experiments with bimodal sediment mixtures (see below).

(ii) Experimental results show that ripples in a sediment mixture are more stable than that in homogeneous sediment of equivalent size, and the ripple length in a mixture is larger than that in homogeneous sediments. To explain these findings, an effective grain size for mixture was used, and a set of refined semi-empirical parameterizations was proposed for the observed ripple characteristics in sediment mixtures [12,14].

(iii) The characteristic grain sorting patterns (Fig. 3), with fine grains accumulating mostly in the ripple troughs and coarse grains on the ripple crests, was observed and explained qualitatively based on the differences in the mobility of sediments and coherent vortex structures. The process of grain sorting was studied by analyzing the time evolution of sediment concentration across ripples (Fig. 4), and a physical explanation was provided [12-14]. Note that grain sorting patterns similar to those observed in the laboratory have been documented in field situations [16].

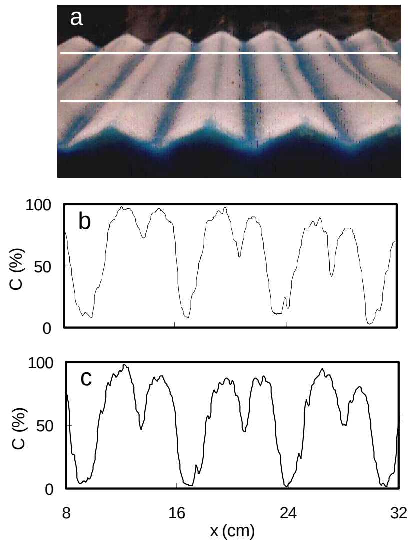

Fig. 3. A photograph (a) and two profiles (b,c) illustrating the coarse sediment concentration C over ripples at two different cross sections [white lines in (a)]. The similarity in the profiles can be clearly seen.

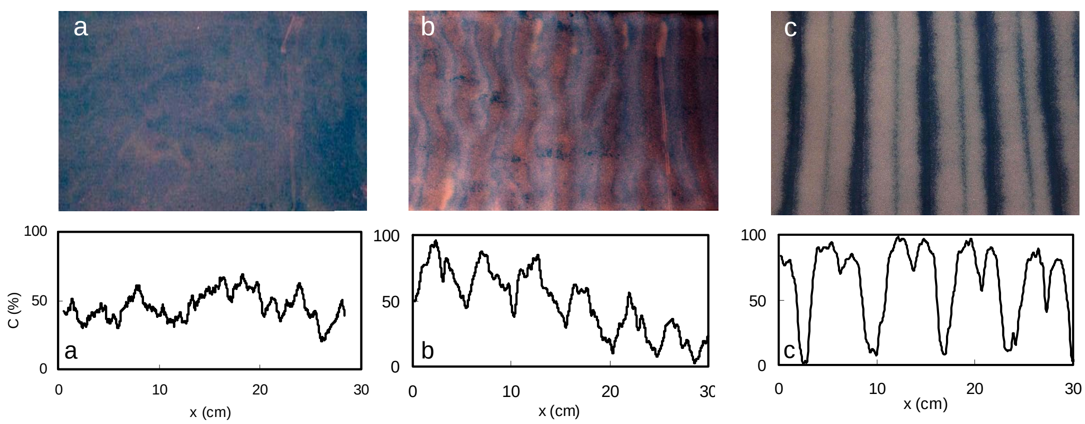

Fig. 4. Time evolution of coarse sediment concentration C across growing (a,b) and established (c) ripples. Starting from a well-mixed bimodal mixture on a flat bed (a), the grain sorting pattern is developing (b) with resulting stable sorting pattern on established ripples (c).

(iv) The results obtained for the ripples decay under weak oscillatory flow (below the threshold for ripple formation), turbulence or a combination thereof show that both weak flow and external zero-mean-flow turbulence can be effective mechanisms for ripple decay. The rate of decay was quantified using the effective ripple diffusivity *K*, which is a function of flow and sediment parameters.

(v) Results on ripple decay under weak oscillatory flow could be modeled to the first approximation by using a time independent effective diffusivity K_0 (see, e.g., Fig. 5a), for which a parameterization was proposed. It was shown that K_0 values are similar for homogeneous and heterogeneous sediments under weak flow, when d^* is used as the equivalent grain diameter of a bimodal mixture.

(vi) To model the ripple decay under turbulence, a variable effective diffusivity K was used (see Fig. 5b). Two plausible mechanisms of sediment transport relevant to ripple decay were identified and were used to explain the observations and to parameterize the diffusivities. First order differences were identified between homogeneous and heterogeneous sediments, however, in that under bedload transport the ripples decay slower in a mixture (smaller K). Nevertheless, under suspended load, the ripples decay at the same rate (similar K) for both a mixture and uniform sediment of equivalent sizes. Quantitative comparison with available field data [17] demonstrated satisfactory agreement between K values [12,14].

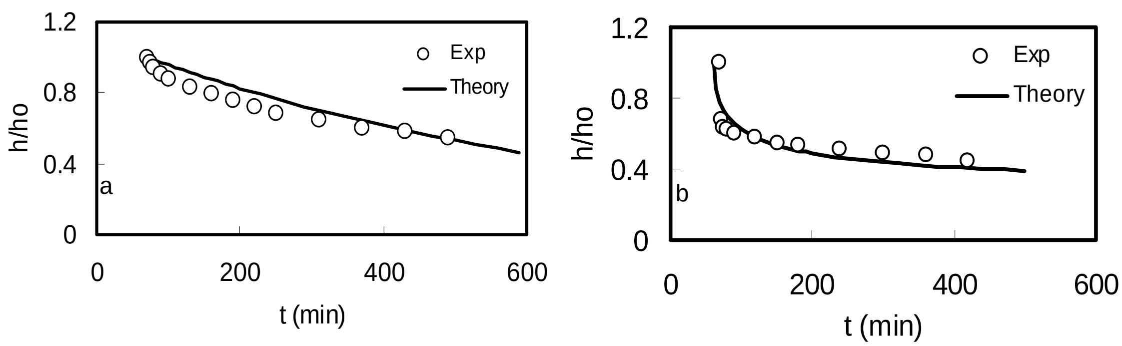

Fig. 5. Ripple diffusion models (solid lines) for ripples decay under weak flow (a) (time independent diffusivity) and background turbulence (b) (variable diffusivity) for the case of bimodal sediments.

IMPACT/APPLICATIONS

Ripple dynamics and sand segregation in heterogeneous sediments under variable forcing, typical of the oceanic coastal zone, are not well understood from a fundamental point of view nor have they been modeled based on phenomenological and physical arguments. Our work has made significant advances in this regard by utilizing integrated laboratory and theoretical/numerical approaches.

TRANSITIONS

We interacted with the field experimental groups of the University of South Florida, Dalhousie University and Woods Hole Oceanographic Institution in comparing field results with predictions based on laboratory results. In closing out our mine burial research conducted under the previous grant, in FY07 we compared laboratory results of scour rate, object burial and flow regimes with operational mine burial models: WISSP, NBURY and DRAMBUIE. The mine scour/burial regime diagram and associated formulations have been transitioned to the Mine Burial Expert System development group at JHU/APL. Experimental data, models and parameterizations developed under this project are being extensively used by the research community (more than 70 journal citations).

RELATED PROJECTS

The PIs are unaware of laboratory projects conducted elsewhere on the decay/degradation of ripples. Studies on sediment segregation on ripples are also sparse, and the PIs are aware of only three papers on this topic [18-20].

HONORS/AWARDS/PRIZES

The PIs work was featured in New York Times on December 25, 2007 and in International Herald Tribune on the December 26, 2007.

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